arXiv:astro-ph/0509445v1 15 Sep 2005

DESIGN CONSIDERATIONS AND SENSITIVITY ESTIMATES FOR AN ACOUSTIC NEUTRINO DETECTOR*

T. KARG, G. ANTON, K. GRAF, J. HÖSSL, A. KAPPES, U. KATZ,
R. LAHMANN, C. NAUMANN AND K. SALOMON

Physikalisches Institut,
Friedrich-Alexander-Universität Erlangen-Nürnberg,
Erwin-Rommel-Straße 1,
91058 Erlangen, Germany
E-mail: Timo.Karg@physik.uni-erlangen.de

We present a Monte Carlo study of an underwater neutrino telescope based on the detection of acoustic signals generated by neutrino induced cascades. This provides a promising approach to instrument large detector volumes needed to detect the small flux of cosmic neutrinos at ultra-high energies ($E \gtrsim 1\,\mathrm{EeV}$). Acoustic signals are calculated based on the thermo-acoustic model. The signal is propagated to the sensors taking frequency dependent attenuation into account, and detected using a threshold trigger, where acoustic background is included as an effective detection threshold. A simple reconstruction algorithm allows for the determination of the cascade direction and energy. Various detector setups are compared regarding their effective volumes. Sensitivity estimates for the diffuse neutrino flux are presented.

1. Introduction

Very large target masses are required to detect the low neutrino fluxes predicted at ultra-high energies. Current water Čerenkov neutrino telescopes (AMANDA, BAIKAL, ANTARES, NESTOR, ...) and next-generation km^3 size detectors (IceCube, KM3NeT) do not have sufficient fiducial volume to detect, for example, GZK neutrinos. The affordable size of these detectors is limited by the attenuation length of light in water or ice which restricts the spacing between optical sensors. G.A. Askariyan described a hydrodynamic mechanism of sound generation for charged particles propagating through water[1] which can be exploited for an acoustic neutrino telescope. The thermo-acoustic model has since been verified in the laboratory several

*This work was supported by the German BMBF Grant No. 05 CN2WE1/2.

times and with high precision[2,3,4]. Utilizing the fact that, for the frequencies considered, the sonic attenuation length in water is about ten times larger than the optical attenuation length, much larger volumes could be instrumented with the same number of sensors. In the next section we describe the simulation chain used for studying acoustic neutrino telescopes. After that, sensitivity estimates for an acoustic detector are derived.

2. The simulation chain

For the simulation an isotropic flux of highest-energy neutrinos ($10^8\,\mathrm{GeV} < E_\nu < 10^{16}\,\mathrm{GeV}$) is generated. Equal numbers of neutrinos are produced in each energy bin of constant width in $\log E$, with a given energy spectrum following a power law (E^{-2}) in each E bin. It is assumed that all neutrinos from above can propagate freely down to the detector. On the other hand, the earth is assumed to be opaque for all neutrinos coming from below the horizon. The elasticity distribution of the neutrino interaction is taken from the ANIS neutrino interaction simulator[5]. For electromagnetic cascades the LPM effect, which elongates the cascade and thus reduces the energy density and the amplitude of the acoustic signal, has to be taken into account. Since there is no reliable shower simulation including the LPM effect in water so far, the leptonic branch of all neutrino interactions is discarded, even for electron-neutrino charged-current interactions.

The three-dimensional cascade development and energy deposition were studied with GEANT4 up to primary hadronic energies of 100 TeV using the QGSP interaction model. The shape and the spatial extension of the energy distribution were found to vary only slightly with the primary energy. Therefore, the spatial distribution of the energy is assumed to be the same for all energies, and the energy density scales linearly with the energy of the hadronic system. This energy distribution and the thermodynamic parameters of water are then used as an input to the thermo-acoustic model which gives the resulting bipolar acoustic signal for every sensor position. The amplitude of the bipolar pulse depends on the cascade energy only.

Sonic attenuation in sea water is strongly frequency dependent. The attenuation length for the typical signal frequency of approx. 20 kHz is 1 km (compared to $50 - 70$ m optical attenuation length relevant for water Čerenkov neutrino telescopes). It is accounted for by applying a frequency filter to the acoustic signal at a given sensor position. Figure 1 shows the parameterization of the amplitude of the bipolar signal as a function of position, which is used in the simulation to determine the sensor response

for a given hadronic cascade.

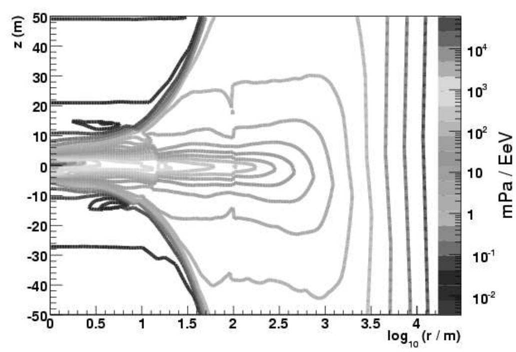

Figure 1. Parameterization of the amplitude of the sonic field for a hadronic cascade centered at the origin. The cascade has a length of approx. 15 m and develops in positive z direction.

The smallest unit of the simulated acoustic detector is an "acoustic module" (AM) which is a device that can detect bipolar acoustic signals above a given detection threshold, p_{th}, determined by the background noise in the sea. Such an AM might be realized as a local array of hydrophones allowing the suppression of background with short correlation length. According to Ref. 6 a threshold of 35 mPa has to be used for a single hydrophone if one allows for one false signal in 10 years at a five-fold coincidence. Using AMs consisting of multiple hydrophones should allow to lower this threshold down to 5 mPa.

Our detector consists of AMs that are arranged randomly inside the instrumented volume in order to avoid geometrical effects on the sensitivity estimates. Neutrino events are generated homogeneously and with 2π sr angular distribution in a volume with a height of 2.5 km (corresponding to typical depths in the Mediterranean Sea), and a radius of 10 km; the resulting generation volume is denoted by V_{gen}. Each AM records the arrival time and amplitude of the signal if it is above the threshold p_{th}. An event is triggered if four or more AMs detect a signal. For our study a timing resolution of 10 μs (100 kHz sampling frequency), a positioning accuracy of 10 cm for the AMs and an amplitude resolution of 2 mPa are implied, which are all realized by Gaussian smearing.

The shower reconstruction is performed in two steps. First, the shower position is reconstructed by minimization of the residuals of the arrival

times assuming an isotropic sonic point source (which is a valid assumption since the typical inter-AM distance is large compared to the shower extension). With this method the cascades center of gravity can be reconstructed with a RMS of 14 cm in each Cartesian coordinate. Based on this position and the parameterization of the sonic field (Fig. 1) the direction and energy of the cascade are reconstructed by minimizing the amplitude residuals. Without applying any selection cuts the median of the error in the direction reconstruction is 7°, where events are still included, for which the reconstruction seems to fail completely. The energy can be determined up to a factor of 3.

3. Sensitivity estimates

Based on the detector simulation chain presented above it is possible to derive sensitivity estimates for various detector configurations. We use the effective volume defined as $V_{\rm eff} = \frac{N_{\rm reco}}{N_{\rm gen}} V_{\rm gen}$ as a measure for the sensitivity of a detector, where $N_{\rm reco}$ is the number of reconstructed events (reconstruction fits converge) without any selection cuts obtained from $N_{\rm gen}$ events generated inside the volume $V_{\rm gen}$. Figure 2 shows the effect of varying the instrumentation density of the detector between 50 and 800 AM/km^3. For densities much lower than approx. 200 AM/km^3 the effective volume drops dramatically at lower energies, and thus, the lower energy threshold rises.

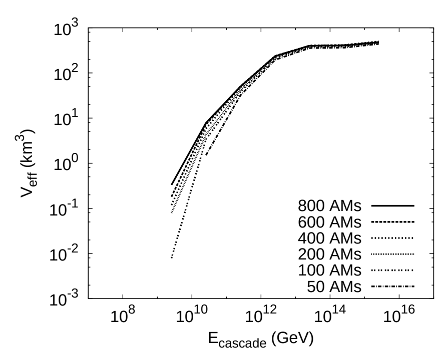

Figure 2. Effective volume for various sensor densities (instrumented volume: 1 km^3).

Further, it is essential for a future acoustic detector to have a pressure threshold $p_{\rm th}$ as low as possible, where the lower limit is given by the intrinsic background noise in the sea which is approx. 1 mPa (sea state 0). On the other hand, a density of only 200 AM/km^3 seems sufficient which

allows to instrument very large volumes with a moderate number of DAQ channels read out at low frequencies (100 kHz), leading to manageable data rates. In figure 3 we show that, with a detector with $3 \cdot 10^5$ DAQ channels ($30\times50\times1\,\mathrm{km}^3$, $200\,\mathrm{AM/km}^3$, $p_{\mathrm{th}} = 5\,\mathrm{mPa}$), several theoretical models that predict neutrinos above 1 EeV could be verified within 5 years of runtime.

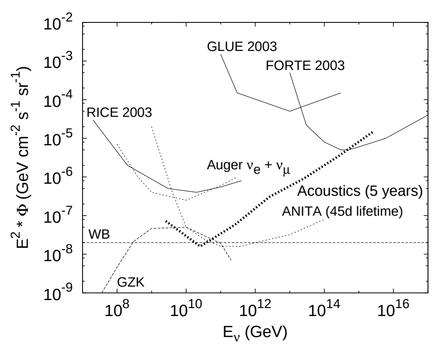

Figure 3. Neutrino flux limit derived for a $30 \times 50 \times 1\,\mathrm{km}^3$ detector with a lifetime of 5 years. Dashed lines are theoretical models (extrapolated Waxman-Bahcall flux and GZK neutrinos). Solid lines are experimental flux limits; dotted lines are expected flux limits from future experiments.

4. Conclusions

Acoustic detection is a promising approach to detect cosmic neutrinos at highest energies. Detectors build of "acoustic modules" that can detect bipolar acoustic signals above 5 mPa are able to reconstruct neutrino-events with energies above 1 EeV with as few as $200\,\mathrm{AM/km}^3$. This allows for the construction of a teraton detector, which is necessary to detect the small neutrino fluxes predicted by theoretical models within a reasonable time.

References

1. G. A. Askariyan, *Atomnaya Energiya* **3**, 152 (1957).
   G. A. Askariyan et al., *Nucl. Inst. Meth.* **164**, 267 (1979).
2. L. Sulak et al., *Nucl. Inst. Meth.* **161**, 203 (1979).
3. S. D. Hunter et al., *J. Acoust. Soc. Am.* **69**, 1557 (1981).
4. K. Graf et al., 1st International ARENA Workshop, Zeuthen (2005).
5. M. Kowalski and A. Gazizov, 28th ICRC, Tsukuba, 1459 (2003).
6. S. Danaher et al., 1st International ARENA Workshop, Zeuthen (2005).